CHAPTER 4

RESEARCH USES OF PROFILERS

Mesoscale meteorology, which focuses on spatial scales ranging from 2 to 2000 km and temporal scales of a few minutes to several hours, has depended traditionally on remote sensing techniques such as satellites and scanning weather radars, e.g., the Geostationary Operational Environmental Satellite (GOES) and Weather Surveillance Radar 1988 Doppler (WSR-88D), to provide the observations. These tools in turn depend mostly on the presence of clouds or precipitation, leaving the extensive and important regions of clear air less well observed, and thus our understanding of mesoscale phenomena less complete. Another limitation of these observing systems has been their inability to directly observe vertical air motion, which is largely responsible for the organization of precipitation. It is now well established that wind profilers provide the most direct measurements of mesoscale vertical air motions in the free troposphere, even in the context of heavy precipitation. Because profilers monitor winds above ground level, they complement the more extensive surface network. This has helped to provide significant insight concerning issues related to decoupling of the surface from the free troposphere in stable conditions, such as produced most nights by the nocturnal boundary layer. In these, and other ways, wind profilers have helped fill important observational gaps, and thus have contributed to our understanding of mesoscale phenomena.

Some key attributes of wind profilers that make them useful in mesoscale meteorological research are

- frequent (hourly or better), continuous wind profiling under nearly all weather conditions (Shapiro et al. 1984; Strauch et al. 1984, 1987; Augustine and Zipser 1987; Wuertz et al. 1988),

- ability to see atmospheric flow above stable boundary layers that otherwise mask conditions aloft (Neiman et al. 1997),

- direct measurement of vertical air motion (Nastrom and Gage 1984; Ralph 1991; Yoe et al. 1992; Moran and Strauch 1994; McAffe et al. 1994, 1995),

- simultaneous measurement of vertical profiles of horizontal wind and precipitation (Fabry et al. 1993; Rogers et al. 1993; Ralph et al. 1995; Cifelli et al. 1996; Neiman et al. 1997), and

- applicability in mesoscale networks (Zamora et al. 1987; Cram et al. 1991; Wilczak et al. 1992; Bluestein and Speheger 1995; Spencer et al. 1996).

Although these key attributes are shared by most types of profilers, not all types are suitable for all problems; e.g., VHF profilers are best for distinguishing between vertical air motions and hydrometeor fall velocities in heavy precipitation, and UHF profilers are best for studies of boundary layer phenomena.

4.1. **Fronts, Jets, and Baroclinic Waves**. Fronts, jets, and baroclinic waves play crucial roles in determining day-to-day weather in midlatitudes. Profilers provide uniquely complete measurements of key features of these systems as they pass through a region. Features include not only changes in the vertical vorticity, divergence, and baroclinicity, but also the vertical air motions forced by these systems (Shapiro et al. 1984; Zamora et al. 1987; Neiman and Shapiro 1989; Crochet et al. 1990; Neiman et al. 1992, 1997; Bluestein and Speheger 1995; Spencer et al. 1996). Identifying precipitation from either the raw Doppler power spectra (e.g., Wakasugi et al. 1986, 1987; Gossard 1988; Rajopadhyaya et al. 1994) or just the spectral moments (Ralph 1995; Williams et al. 1995; Ralph et al. 1995, 1996) has also permitted the important kinematic wind features to be related to the distribution of precipitation (Fabry et al. 1993; Rogers et al. 1993; Ralph et al. 1995; Marwitz et al. 1997; Neiman et al. 1997). An example of using spectral moment data to identify precipitation is shown in Fig. 4-1 from Ralph et al. (1995). Even a baroclinic zone aloft can be clearly revealed by easily monitoring the height of the melting layer as a function of time (Neiman et al. 1995, 1997). Among numerous other contributions, these data have led to a clearer view of the structure of fronts extending from the surface to the tropopause, including both precipitating and clear regions. This approach has yielded new understanding of the relationship between cold fronts and prefrontal squall lines where the latent heating and cooling occurs fully on the warm side of a strong cold front (Neiman et al. 1997). It has also provided clear evidence of strong and deep vertical motions even in dry fronts (Ralph et al. 1993a). Results from studies of cold fronts aloft and observations of multiple frontal zones and their mergers are presented by Neiman et al. (1997).

4.2. **Gravity Waves**. Atmospheric gravity waves are characterized by circulations containing horizontal convergence/divergence and vertical motions. They can propagate horizontally if they are ducted, or vertically. They contribute to vertical and horizontal fluxes of momentum, and can also organize clouds and precipitation. Wind profilers have provided unique measurements of these processes, including documentation of the spectrum of atmospheric motions (e.g., VanZandt 1982, 1985; Gage and Nastrom 1985; Fritts and VanZandt 1987; Fritts et al. 1988; Carter et al. 1989; VanZandt et al. 1991). Most of these and other early profiler-based gravity wave studies are summarized nicely by Gage (1990). More recent progress includes quantitative assessments of vertical fluxes crucial to the atmospheric momentum balance on a global scale (Prichard and Thomas 1993; Worthington and Thomas 1996). For example, the first observations of the complete structure of a gravity wave in a duct involving a critical layer were provided by the profiler's vertical velocity measurement capability, and by operation in both clear and precipitating conditions (Ralph et al. 1993b). Profilers helped identify mountains, fronts, upper-level jets, and convection as sources of gravity waves, and quantified their relative importance (Nastrom et al. 1987, 1990; Ralph et al. 1993a; Jin et al. 1996). The production of turbulence in the clear air due to critical levels associated with mountain waves has now been clearly demonstrated (Prichard et al. 1995). Changes in vertical motions observed downstream of mountains have illustrated and quantified that mountain waves can be highly nonstationary, even though theory has been concerned primarily with stationary conditions (Ralph et al. 1992, 1997; Caccia et al. 1997). This has brought into question key earlier findings concerning the impact of mountains on the global atmospheric momentum balance.

4.3. **Convective Storms**. Unlike conventional Doppler weather radars, wind profilers (especially VHF profilers) have provided the best measurements of vertical air motion within convective storms because the air motion and hydrometeor fall velocities can be distinguished from one another. This and the horizontal wind information are used to explore the relationship between air motions within the storm and the microphysics (Wakasugi et al. 1986, 1987; Augustine and Zipser 1987; Gossard 1988; Ralph et al. 1993b; Cifelli and Rutledge 1994; Rajopadhyaya et al. 1994; Williams et al. 1995; Cifelli et al. 1996; May and Rajopadhyaya 1996). Profilers have also been used to document the mesoscale environment associated with severe convection, including vorticity and divergence calculated from a triangle of profilers (Wilczak et al. 1992), and the generation of the Denver Cyclone, which is a key feature responsible for the organization of severe convection near Denver, Colorado (Wilczak and Glendening 1988; Wilczak and Christian 1990). Hourly wind profiler data have also been used to study helicity as a tornado forecast parameter (Davies-Jones et al. 1990; Morris 1993).

4.4. **Coastal Weather**. Despite the high population density along the west coast of the United States, the region suffers from inadequate observations. Wind profilers along the coast have provided crucial documentation of land-falling winter storms (Neiman et al. 1995) and of strong wind shifts that propagate northward along the coast during summer (Ralph et al. 1998). These data also make it possible to increase our understanding of the typical diurnal cycle by extending earlier studies that could not continuously measure conditions above the surface, using techniques based on an earlier boundary layer climatology over Colorado (May and Wilczak 1993). Several current sites on islands offshore add greatly to the potential of this dataset. For example, profiler and RASS data helped establish that the coastal surges during summer are best characterized by a three-layer system rather than a two-layer system, because of the surprising observation that the marine boundary layer depth did not change significantly during the initial passage of the disturbance (Ralph et al. 1998).

4.5. **Air Quality Monitoring**. Although Doppler sodars (acoustic sounders) have filled an essential role in air quality observations, their limited vertical range has been a disappointment for applications where information above the boundary layer is required. The boundary layer profiler developed by Ecklund et al. (1988) has overcome these limitations. This instrument has been deployed extensively in mesoscale air quality research programs (Neff 1994). Its low cost, and portability, have made it the instrument of choice for low-altitude atmospheric research and monitoring of mean wind, temperature, and mixing depth.

A limitation on the deployment of wind profilers in urban areas is their susceptibility to clutter contamination. Recent advances in clutter-screen design, diffraction reduction, and signal processing such as wavelet transforms applied to raw radar time series data (Jordan et al. 1997) portend significant advances in the capability of wind profilers to operate over a much broader range of environmental conditions.

The combination of RASS and wind profilers has proved valuable in the challenging measurement of temperature and mixed-layer profiles in urban areas. RASS rarely provides sufficient height coverage in deep, mixed layers (between 500 and 1500 m for 915-MHz-based systems), but when it is combined with the radar reflectivity profile, good mixing-depth comparisons using airborne aerosol lidar measurements are obtained (White et al. 1998). In these applications, it is necessary to collocate the profiler with a laser ceilometer so as to identify cloudy conditions. A payoff in the collocation of such instruments is the ability of the profiler to see into the cloud systems and determine the potential for cloud-venting of pollutants.

Measurements in the nocturnal boundary layer are important to characterize the deposition of pollutants to the surface as well as to determine the degree of isolation of the surface layer from the residual layer. Where the minimum range and coarse resolution (typically 150-m minimum range and 60-m resolution) of radar wind profilers is inadequate, monostatic sodars can be used to help interpret boundary layer processes (e.g., Beyrich and Gorsdorf 1995).

4.6. **Global Climate Research**. Profilers became widely used for climate observations, especially during the Tropical Ocean Global Atmosphere (TOGA) decade (1985–1994). The TOGA Program began in 1985 with an objective of improving observations of the coupled ocean-atmosphere system, particularly those that relate to the El Niño/Southern Oscillation (ENSO) phenomenon (McPhaden et al. 1997). Profilers have been used in numerous field campaigns in the last decade, most notably as part of the ISSs specially designed for the TOGA Coupled Ocean-Atmosphere Response Experiment (COARE) (Parsons et al. 1994).

Profilers were recognized at the beginning of TOGA by NOAA's Office of Global Programs as a cost-effective means to obtain wind information over the data-sparse equatorial Pacific Ocean. Reliable wind measurements in real time from remote islands in the tropical Pacific were demonstrated first at Christmas Island, Kiribati, using a 50-MHz wind profiler (Gage et al. 1988, 1994a) and later using a 915-MHz wind profiler (Carter et al. 1995). This profiler has provided tropospheric wind observations nearly continuously for more than a decade. Because it is incapable of measuring wind below 1.5 km, NOAA's Aeronomy Laboratory developed a UHF lower tropospheric wind profiler (Ecklund et al. 1988; Carter et al. 1995) to fill the low-level gap.

An important part of the TOGA observing system is the Trans-Pacific Profiler Network (TPPN) completed just prior to the end of TOGA. The TPPN extends from Indonesia on the west to Peru on the west coast of South America, as shown in Fig. 4-2. The continued operation of the TPPN relies upon the collaboration and cooperation of interested parties in the countries of Peru, Ecuador, Kiribati, Nauru, Papua New Guinea, and Indonesia. The principal collaborators are currently the University of Colorado/Cooperative Institute for Research in Environmental Sciences (CIRES) and the NOAA Aeronomy Laboratory.

The Christmas Island profiler has been in operation long enough to provide a record of the variability of winds over the central Pacific on the interannual time scale pertinent to ENSO. Gage et al. (1996b) analyzed the zonal winds observed at Christmas Island and noted a robust annual cycle modulated by the ENSO cycle. During the northern winter months, upper tropospheric westerlies are dominant during non-El Niño years. These upper tropospheric westerlies are thought to be related to the Walker circulation and are strongest during La Niña when convection is most active over the warm-pool region of the western Pacific. During El Niño when the convection moves eastward into the central Pacific, the upper tropospheric winds are replaced for the most part by easterlies. The occurrence of upper tropospheric westerlies is of considerable importance in tropical dynamics because they provide a duct for midtropospheric disturbances to propagate into the equatorial zone (Webster and Holton 1982).

Profilers also provide direct measurements of vertical motions in the tropics (Balsley et al. 1988; Gage et al. 1991; Huaman and Balsley 1996). The direct, long-term, measurements of vertical motions are unique. They help explain the heat balance in the tropical atmosphere because the vertical motions give the component of adiabatic heating and cooling that largely balances diabatic heating and cooling (Gage et al. 1991). Although Nastrom and VanZandt (1994) have shown that at midlatitudes directly measured vertical motions are often biased by internal gravity waves, the level of gravity waves is small enough in the tropical atmosphere to permit unbiased measurement of vertical motions on the order of 0.01 m s^{-1} (Huaman and Balsley 1996).

The hydrological cycle is a very important component of the earth-ocean-atmosphere climate system that is only poorly observed and simulated in numerical models (Webster 1994). Profilers provide the kind of observations needed to improve our ability to quantify the hydrological cycle. For example, the moisture flux must be well measured to close the water budget. Good moisture flux measurements require both humidity and wind measurements in the lower troposphere. UHF profilers are proven tools for improving moisture flux measurements. Their contribution to water budget calculations during the TOGA COARE Intensive Observing Period (IOP) is reported in Ciesielski et al. (1997).

Another crucial element of the hydrological cycle is precipitation. Atmospheric models do not resolve the hydrological cycle very well, partly because they must parameterize convection as a subgrid-scale process. Eventually, precipitation must be estimated on a global basis by satellites, but the satellite observations themselves must be calibrated and validated. UHF profilers are excellent tools for observing the vertical structure and evolution of precipitating cloud systems (Gage et al. 1994a,b, 1996a; Ecklund and Gage 1995) and can be used to provide vertically resolved estimates of the mass flux of precipitation. Observations in the tropics have been used for classification of precipitation into convective and stratiform components (Williams et al. 1995). Because profilers observe continuously, they provide the needed data to derive the diurnal cycle of precipitation.

Island- and ship-based profilers have recently been used in the Combined Sensor Program (CSP) sponsored by the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Program to clarify the influence of islands on clouds and precipitation (Post et al. 1997). Profilers continue to play a vital role in monitoring atmospheric winds in data-sparse regions of the tropical Pacific and are an important part of the DOE/ARM tropical western Pacific Atmospheric Radiation and Cloud Station (ARCS) currently installed at Manus Island, Papua New Guinea. A continental component of the DOE program is located at the center of the NPN in Oklahoma. This southern Great Plains ARM Cloud and Radiation Testbed (CART) site employs three 915-MHz RASS-equipped profilers and one 50-MHz profiler (Stokes and Schwartz 1994).

4.7. **Turbulence Measurements**. While the mean winds measured by wind profilers are quite useful, they are only part of the information required for many studies of the atmosphere. For example, air pollution or dispersion models may require velocity variances, momentum and scalar fluxes, and convective mixed-layer depth. The structure function parameters, C_x^2, where x could be velocity (u, v, or w), temperature (T), humidity (Q), or refractive index (n), are also useful statistics for describing the turbulent structure of the atmosphere. The appropriate structure function parameters are related to the turbulent kinetic energy (TKE) and scalar dissipation rates (Corrsin 1951). All these turbulence variables have been measured, with varying degrees of success, using wind profilers. A small portion of that research is highlighted here along with some of the problems facing the researcher. A more complete review of the subject is given by Gage (1990). Figure 4-3 shows examples of turbulence data taken in the CBL with the NOAA 915-MHz wind profiler.

The measurement of C_n^2 from radar backscatter is described formally in many standard texts (e.g., Battan 1973; Gossard and Strauch 1983; Doviak and Zrníc 1984). To obtain quantitatively accurate results, a wind profiler must be calibrated. The calibration depends on assumptions about the transmitted beam and on properties of the radar hardware, including antenna efficiency and receiver bandwidth. Methods to calculate C_u^2 from wind profiler measurements are described by Hocking (1985), Gossard et al. (1990), and Cohn (1995). Part of the problem with validating these techniques has been the lack of direct observations available for comparison. White (1996) found C_u^2 measurements in the CBL obtained from a sonic anemometer mounted on a 300-m tower and from a 915-MHz wind profiler to be only moderately correlated (r = 0.7).

The depth of the CBL is a critical parameter for dispersion modeling, but it is difficult to parameterize accurately. A comparison of different in situ and remote sensing techniques for detecting the depth of the CBL was given by Kaimal et al. (1982). The remote sensors used in that study consisted of two radars (X-band and FM-CW), a sodar, and a lidar. White (1993) and Angevine et al. (1994) demonstrated a similar capability for the 915-MHz wind profilers. The technique is based on experimental and theoretical evidence indicating that the profile of C_n^2 exhibits a peak at the inversion capping the mixed layer.

Entrainment is an important but physically intractable process related to boundary layer growth. The entrainment velocity is defined as the difference between the total time rate of change of the boundary layer depth and the average vertical velocity at the top of the boundary layer. Angevine et al. (1998) found reasonable rates of entrainment using a triangle of wind profilers. The vertical velocity at the top of the boundary layer was found by vertically integrating the horizontal wind divergence calculated from the hourly wind profiles measured at the corners of the triangle. Radar backscatter data were used to determine the evolution of boundary layer height. White et al. (1991) explored a different technique in which they used the structure function parameters measured by a 404-MHz wind profiler in conjunction with the interfacial-layer model of Wyngaard and LeMone

(1980) to estimate the entrainment velocity. White et al. (1991) relied on rawinsondes to provide the jumps in temperature and humidity in the interfacial layer and the lapse rate of temperature above the inversion required by the model. However, a wind profiler equipped with RASS could provide the necessary temperature measurements, and as discussed in section 4.8, the same wind profiler/RASS combination can be used to estimate humidity gradients aloft.

Angevine et al. (1993a,b) examined the possibility of using a wind profiler with RASS to measure profiles of virtual temperature flux and momentum flux. The temperature flux was calculated by the method of Peters et al. (1985), which does not include correlating temperature with vertical velocity at zero lag, because errors in the vertical velocity are directly correlated with errors in the virtual temperatures retrieved from RASS. The momentum flux was computed by the variance differencing technique of Vincent and Reid (1983). The wind profiler virtual temperature flux estimates agreed more favorably with aircraft measurements than did the wind profiler momentum flux estimates. For the latter, Angevine (1993b) concluded that additional research was needed to establish the feasibility of the wind profiler technique.

It is indeed possible to take the time series of velocity components measured with a wind profiler and calculate variances, covariances, and even higher-order moments. However, the finite sampling volume imposes a low-pass filter on the spatial structure of turbulence measured. The velocity fluctuations are also averaged over a finite averaging time, which imposes additional low-pass filtering on the fluctuations. White (1996) demonstrated the effect of these sampling filters by comparing the vertical velocity fluctuations measured by a 915-MHz wind profiler and a sonic anemometer. The high-frequency structure is recoverable, in theory, because lines in the Doppler velocity spectrum are broadened by the unresolved frequencies. Unfortunately, additional factors other than turbulence contribute to spectral broadening, which make it difficult to diagnose the turbulence contribution. Corrections to account for these factors are given by Gossard (1990).

Some of the same problems that affect the performance of wind profilers for mean wind profiling also pertain to turbulence applications, because both make use of the moments generated from the Doppler velocity spectrum. The foremost problem is the interfering signals received from nonatmospheric targets. The integrity of the spectral moments depends on the ability of the radar signal processing algorithm to recognize and remove the contaminating signals. Other problems are related to signal processing strategies, which traditionally have been designed to maximize the performance for mean wind profiling rather than for turbulence applications. For example, spectral averaging is often applied before the Doppler velocities are calculated. This process increases the detectability of the signal and ultimately improves the height coverage of the mean wind profiles produced by a consensus algorithm. However, this process also increases the dwell time, which in turn increases the low-pass filtering of the turbulence. It is also common to clip the spectral energy from the zero-velocity spectral bin in the Doppler velocity spectrum automatically to reduce the impact of ground clutter. As demonstrated by White (1996), this procedure introduces a bias in the mean vertical velocity calculated from wind profiler time series in the CBL. The problem is exacerbated by using too few spectral points to resolve the Doppler velocity spectrum, further evidence that new data processing techniques are needed to enhance the utility of profilers.

The results from previous studies are encouraging, suggesting that we should continue to evaluate and validate techniques to measure turbulence variables with wind profilers. We must also consider the limitations of wind profilers for turbulence applications, particularly the spatial and temporal averaging inherent in the sampling. If these techniques prove to be viable, the turbulence profiles measured by wind profilers could be used, for example, to evaluate the performance of the boundary layer parameterizations contained in mesoscale numerical models (e.g., Burk and Thompson 1989) and the turbulence structure inferred from large-eddy simulation (e.g., Peltier and Wyngaard 1995). One reason for optimism is the current commitment by research institutions and commercial vendors to improve wind profiler signal processing.

4.8. **Moisture Profiling**. Backscattered power from vertically pointing Doppler radars has long been recognized as providing an excellent representation of profiles of the gradient of atmospheric refractive index (e.g., Friend 1949; Saxton et al. 1964; Ottersten 1969; Richter 1969; Gossard et al. 1970; Chadwick and Gossard 1983; Gossard 1990). Recent experiments in southern California have demonstrated very high correlation between the radar-measured refractive index structure parameter and the square of the radiosonde-measured potential refractive index gradient (Gossard et al. 1997). In the lower troposphere, refractive index fluctuations are due almost entirely to fluctuations in specific humidity. Thus, profiles of specific humidity are very highly correlated to profiles of potential refractive index in the lower atmosphere. The challenge is to generalize the empirical correlation with an improved description of the physical relationships between radar-measured quantities and other meteorological parameters. The formal calculation of the humidity gradient from radar-measured parameters leads to a prediction of the square of the humidity gradient, and thus loses the sign of the gradient. Therefore, the sign of the gradient must be determined by other constraints such as virtual temperature profiles derived from RASS, total precipitable water derived from global positioning system (GPS) measurements, and numerical models.

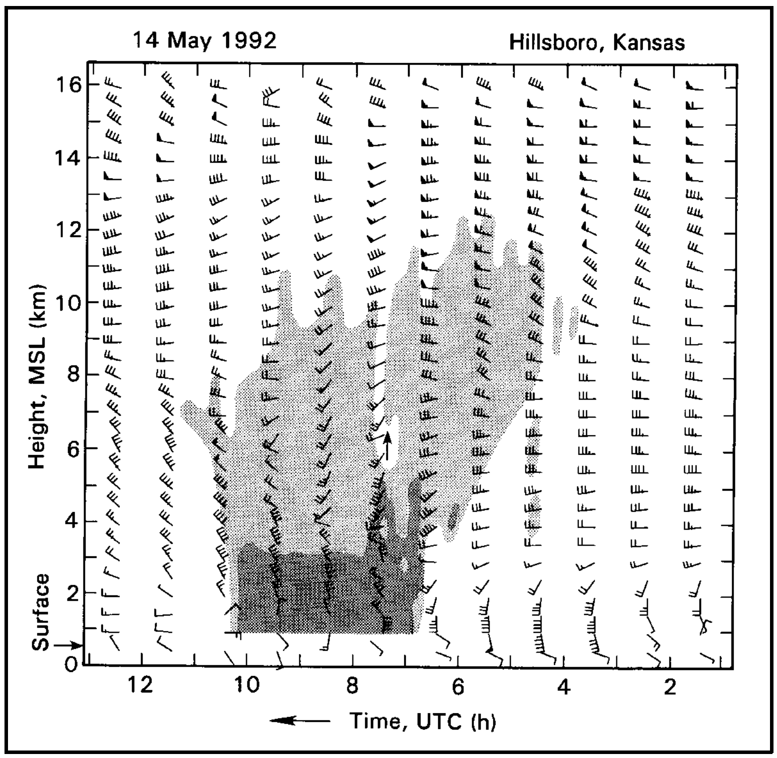

Figure 4-1. Time-height cross section of hourly averaged horizontal winds observed by the Hillsboro, Kansas, profiler on 14 May 1992. For clarity, only every other range gate is plotted. Regions of snow (0.7 m s^{-1} < V_r < 3.0 m s^{-1}, light shading) and rain (V_r > 3.0 m s^{-1}, dark shading), as determined from the spectral moment data, are highlighted. V_r is fall velocity (vertical) of the hydrometeors. The arrow represents a convective updraft within the storm. [From Ralph et al. (1995).]

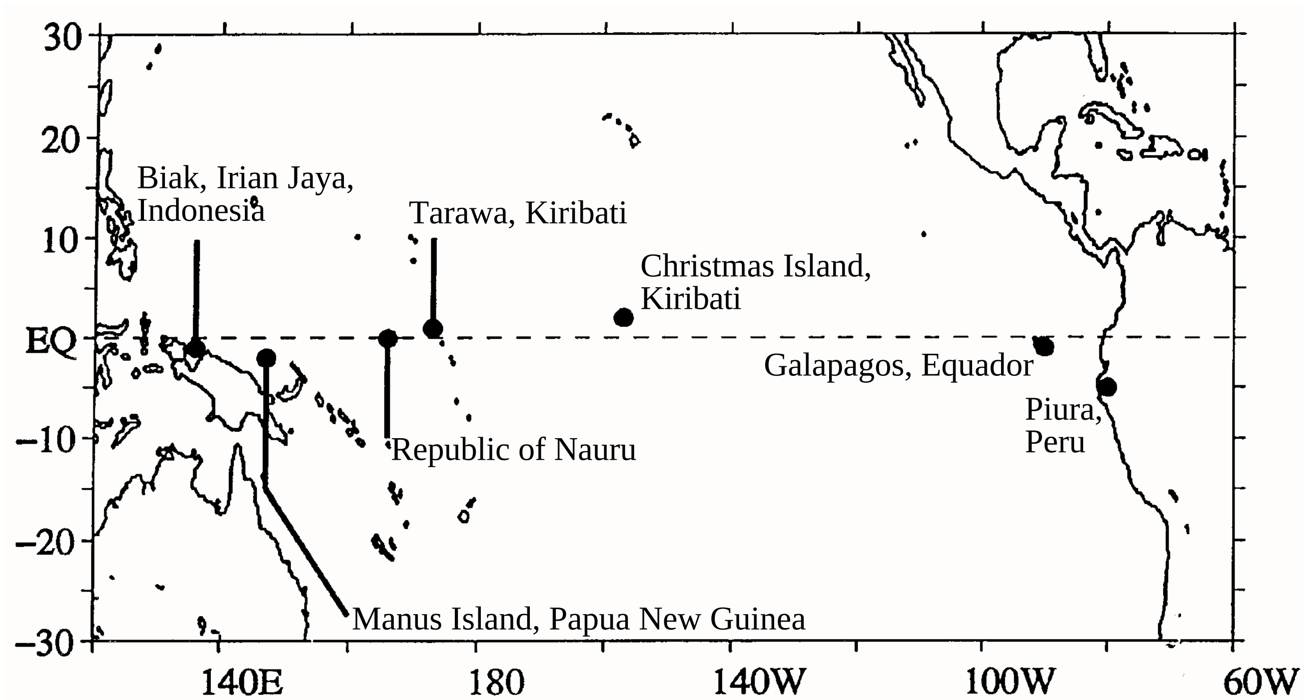

Figure 4-2. The Trans-Pacific Profiler Network (TPPN) completed just prior to the end of TOGA. The TPPN extends from Indonesia on the west to Peru on the west coast of South America.

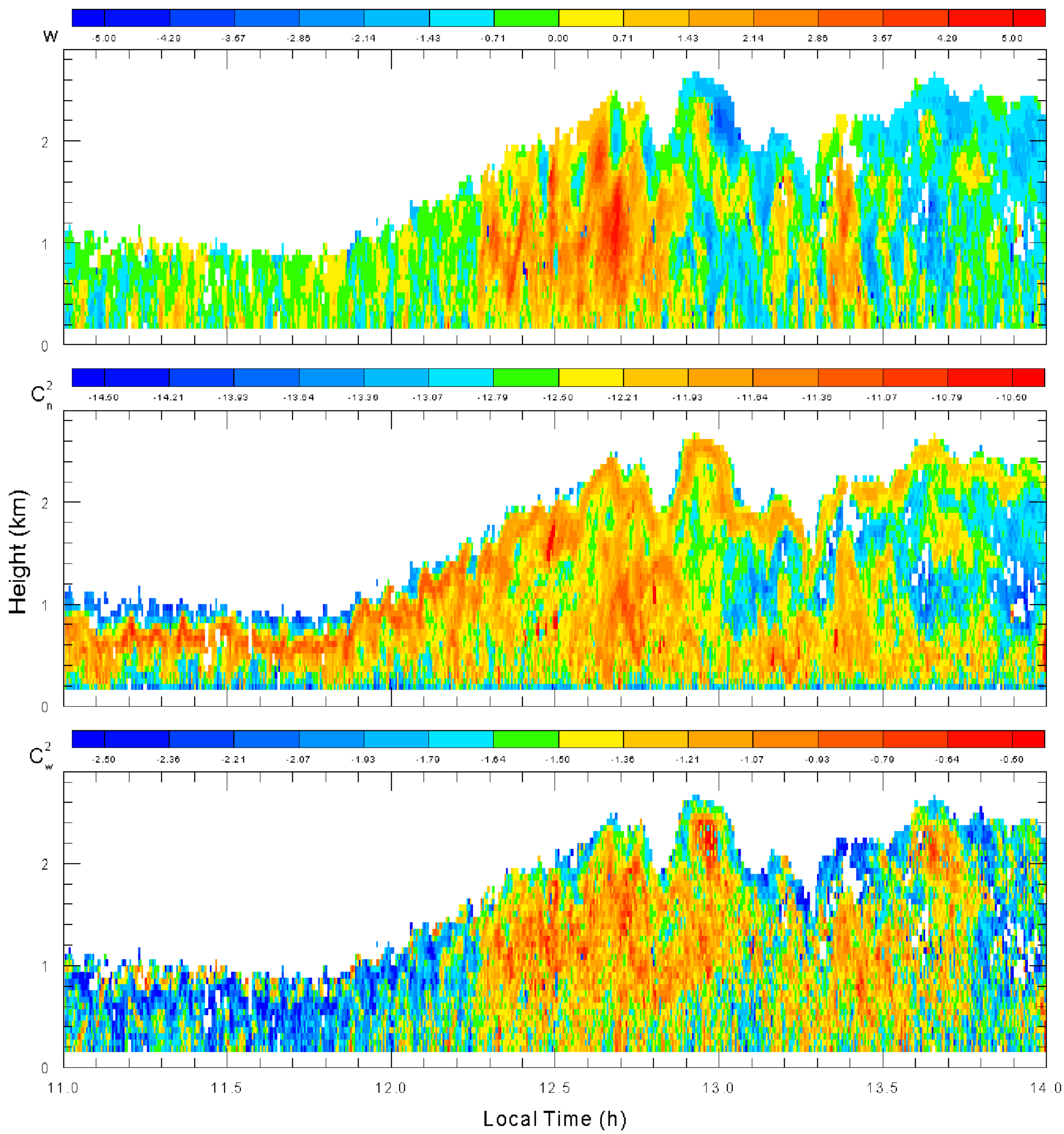

Figure 4-3. Time-height profiles of vertical velocity (top), C_n^2 (middle), and C_w^2 (bottom) depicting a rapidly evolving CBL. These measurements were taken with the NOAA 915-MHz wind profiler at Erie, Colorado, on 16 July 1993 from 1100 to 1400 MST. For this case, the wind profiler was programmed to obtain vertical profiles only with 60-m vertical resolution and 15-s temporal resolution.